Severe Operational Loads in Rudder-induced Maneuvers

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Rudder and Lateral Control Events Initiative

- Driven by concerns arising from crash of Airbus A300-600, AA587, New York, 2001
- Separate activity from OLMP
  - Coordinated by IATA
  - To identify the limited number of high-load events, rather than operational statistics over a large number of flights
- Seeks better understanding of all potential factors contributing to rudder incidents and accidents
  - Adequacy of airworthiness requirements.
  - Control system design criteria.
  - Human factors
  - Trigger events leading to problem (stall departure, system malfunction, turbulence, confusion,.....)

Rudder Kick – The Regulatory Requirement

FAR/JAR 25.351 ; Yaw maneuver

Response to a single abrupt maximum rudder application at any speed between V_{MC} and V_D

- Pilot foot force is nowhere less than 200 lb
  - equals fully saturated control input on all power-operated control systems, where typical max rudder < 100 lb
- Flat yaw considered ; Aileron is used as needed for wings level
  - note that full aileron may be marginally sufficient at low airspeed
- Rudder "on the stops" until a steady sideslip condition is attained
- Rudder is then rapidly centralized ; Aircraft yaws back towards straight and level flight

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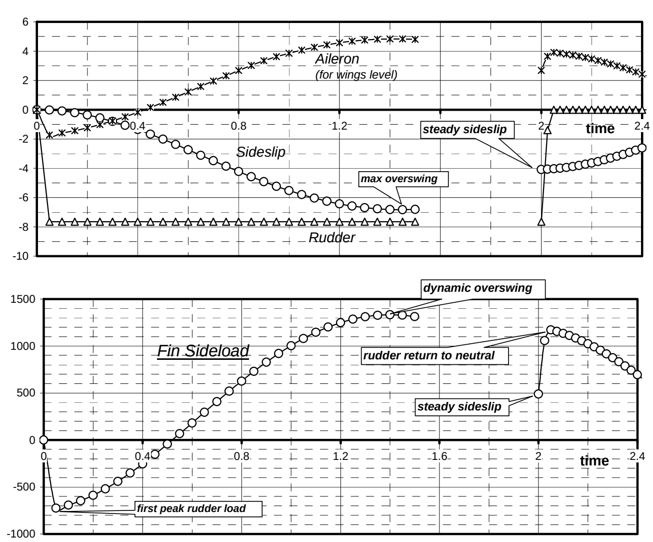
Design Rudder Kick Maneuver ; FAR 25.351

(Typical ; 270 knots)



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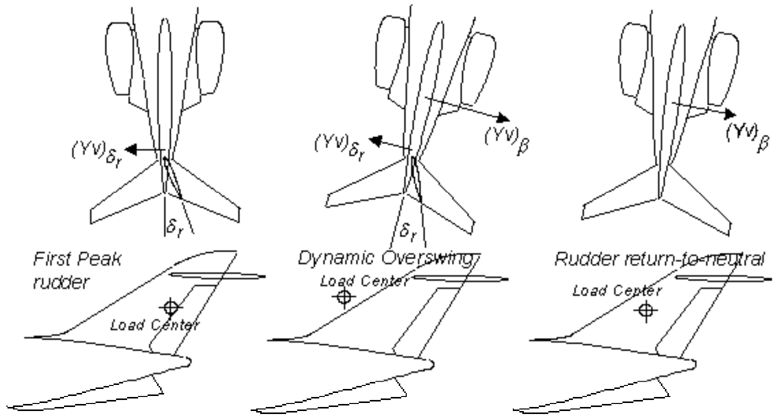
Rudder-Induced Operational Loads

Rudder Kick and Rudder Return-to-neutral
Significant Vertical Tail Loading Actions



Aft loading Forward loading Mid loading

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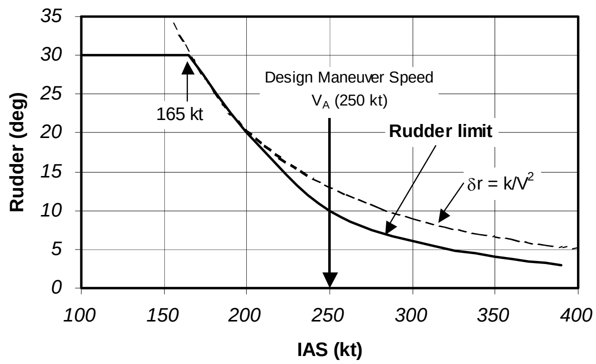
A300-600 Rudder Limiter



- Limiting begins at 165 kt. (pretty slow !)
- Loads due to full rudder only reduce below 165 kt (rudder on hard stops)
- Similar maximum rudder loads at any speed above 165 kt
  - Maneuver speed V_A is not relevant to the loads experienced.

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Rudder Limiter Systems

(with typical forces and displacements)

- Rudder has to be powerful at low airspeed
  - normally sized for low-speed engine out / crosswind approach
- But large rudder deflections are not needed at typical flight speeds
  - Loads, and severity of response, increase as square of airspeed
  - Limiter systems are adopted in lieu of the pilot effort limitation which would apply with manual controls

Type	Aircraft	Implementation	Rudder displacement		Pedal Movement and Pedal force		Pedal feel force by….
			Low speed	High speed	Low speed	High speed	
Variable stop	A300-600 A310, A320, A330, A340 MD80	Mechanized input limiter (eg pedal stop) as a function of airspeed	30 deg	< 6 deg	5 in / 65 lb	1 in / 20 lb	Artificial feel ; Mechanical spring + friction
Actuator stall	B707,B727, B737 DC10, MD11	Hydraulic actuator blowdown	30 deg	< 6 deg	5 in / 65 lb	1 in / 20 lb	Artificial feel ; Mechanical spring + friction
Ratio changer	B747, B757, B767, Early A300	Variable length input crank	30 deg	< 6 deg	5 in / 65 lb	<= same	Artificial feel ; Mechanical spring + friction
FBW	B777, A340-500	software	30 deg	< 6 deg	5 in / 65 lb	<= same	Artificial feel ; Mechanical spring + friction

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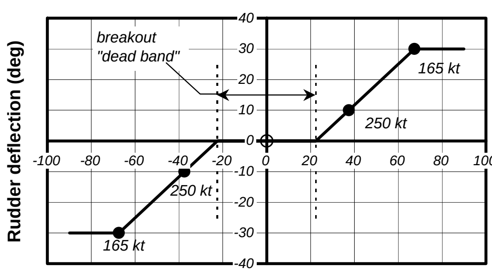
A300-600 Rudder Feel

(Typical of most aircraft without rudder ratio changers)



IAS (kt)	Pedal movement (inch)	Pedal force (pound)	Rudder limit (deg)
165	5 inch	67 lb	30 deg
250	1.7 inch	37 lb	10 deg
350	0.7 inch	28.5 lb	4 deg

- Requires a 22 pound pedal break-out force at all speeds
- Increased rudder pedal sensitivity at high speed is a possible issue
  - although operational use of max rudder at high speed is rare.

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Dutch Roll

The naturally damped roll and yaw motion which results following any yaw disturbance, such as a lateral gust or rudder kick.

- Period for one full cycle is of order 6 sec (large transport aircraft) to 3 seconds (business jet)
- Usually is a lightly damped mode.
- There is a resonant increase in amplitude if the motion is "forced" at dutch roll frequency.
  - otherwise damps out after several cycles
- Aerodynamic coupling between yaw and roll is strong, particularly for swept wing aircraft
  - Yaw induces roll - with delayed action relative to rudder.

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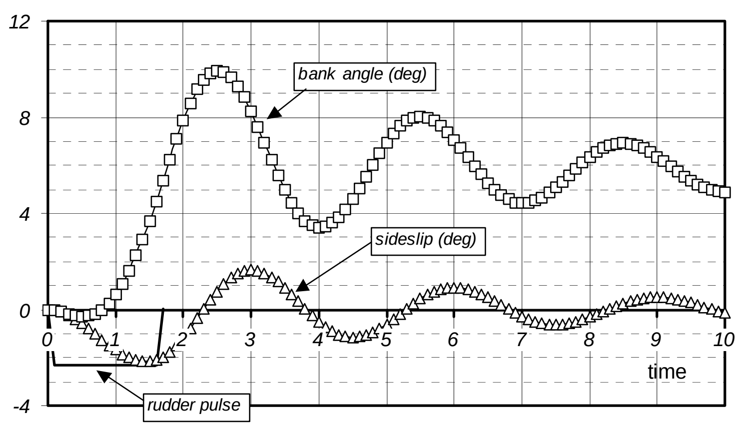
Dutch Roll

Lightly damped oscillation in roll and yaw
Sample data : 3 second period
3.5 seconds to half amplitude



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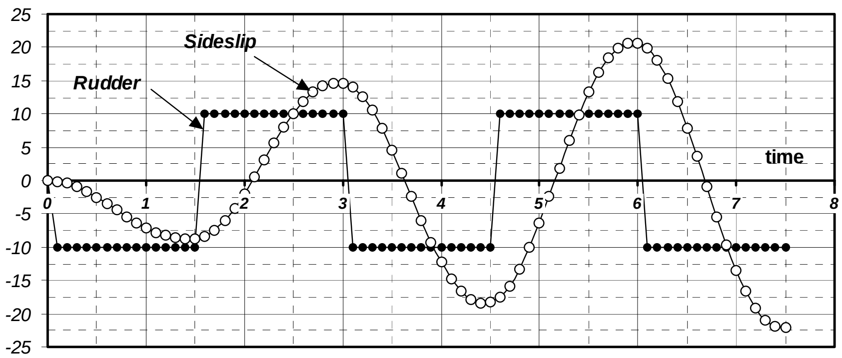
Multiple Rudder Reversals

- at dutch roll frequency , yaw damper off -



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Yaw Damper Effects

- All transport aircraft incorporate automatic yaw-damper systems
  - they sense aircraft yaw rate and apply small amounts of rudder to oppose the motion
  - Don't cause the pedals to move – pilot is unaware of the function
  - Limited authority
- Damps gust response, improves ride comfort and pilot tracking performance.
- There may also be a turn coordination system to minimize adverse yaw when turning.
- Although not intended for the purpose, yaw dampers will tend to alleviate any pilot-commanded yawing response
  - There can be significantly less yaw build-up and fin loading in a series of rudder reversals.
  - <u>but only if rudder input signal is not saturated by full pilot rudder command</u>.

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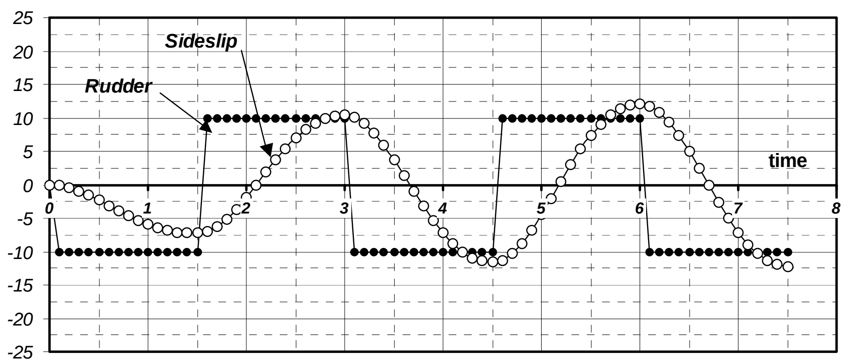
Rudder-Induced Operational Loads

Multiple Rudder Reversals

- at dutch roll frequency , yaw damper on -



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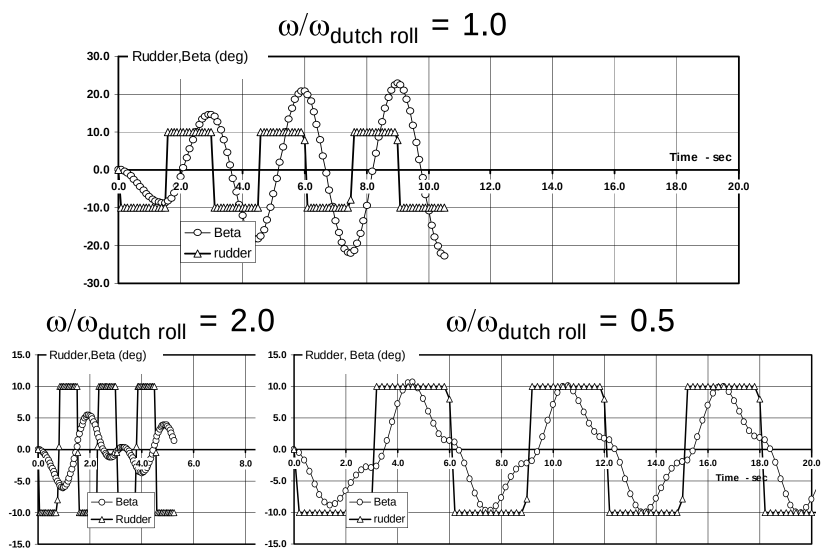
Resonant Response at Dutch Roll Frequency (YD off)



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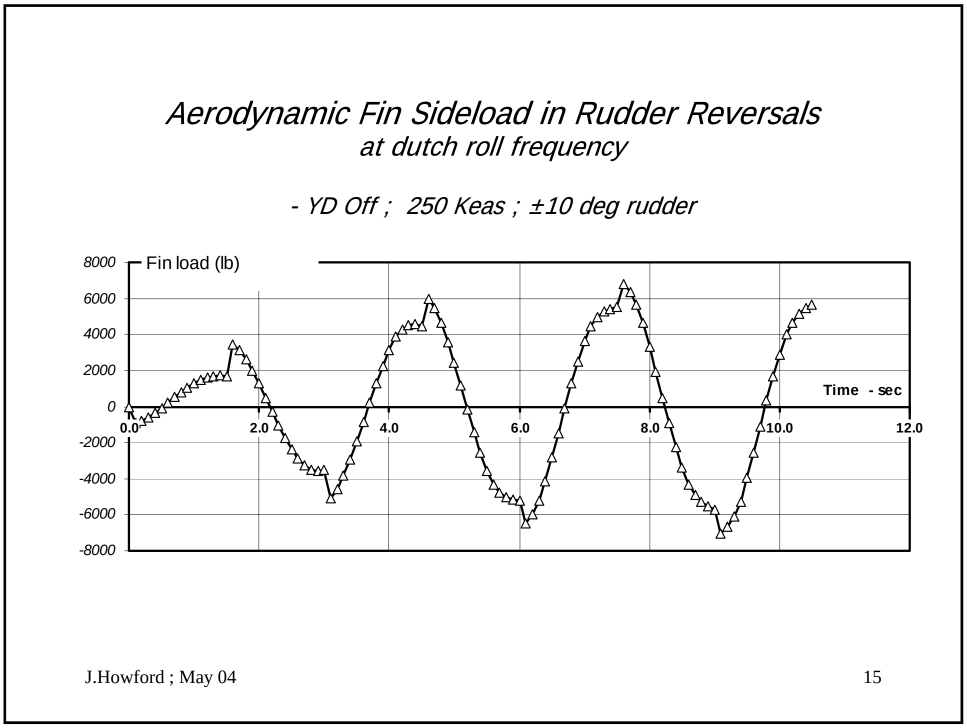
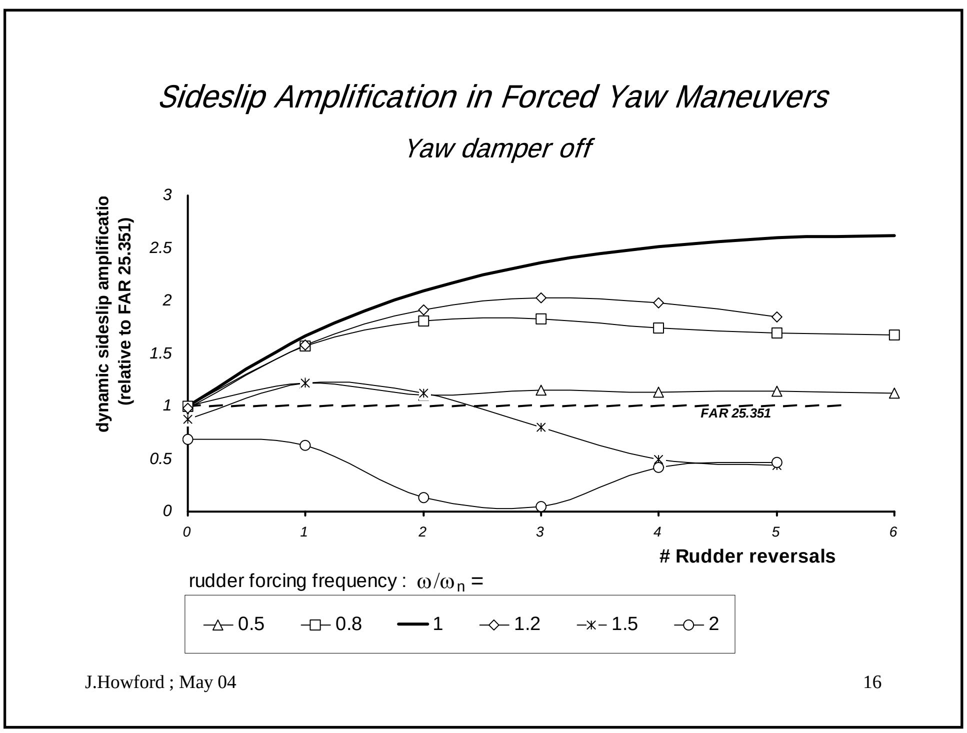
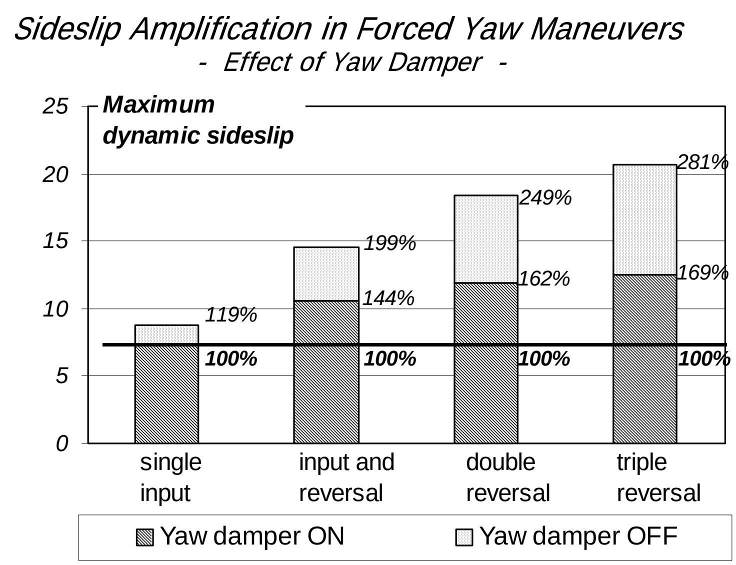
Rudder-Induced Operational Loads





Rudder-Induced Operational Loads



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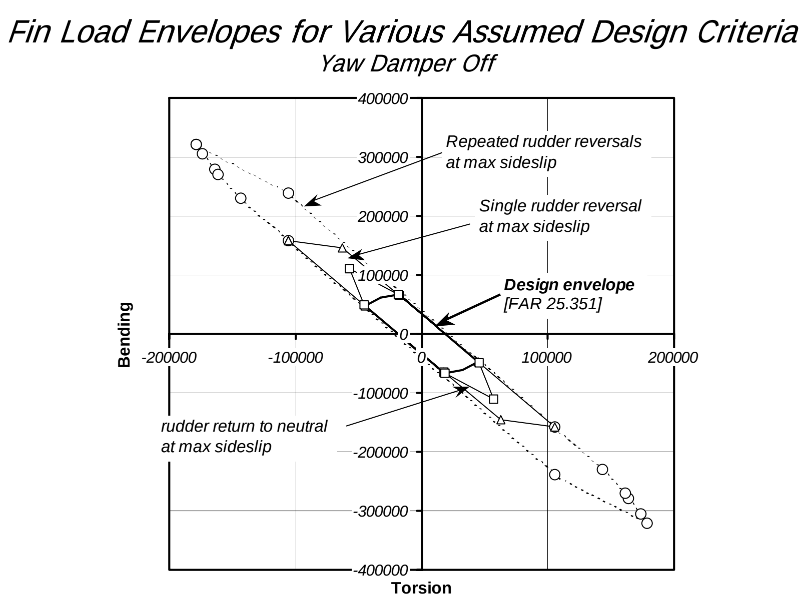

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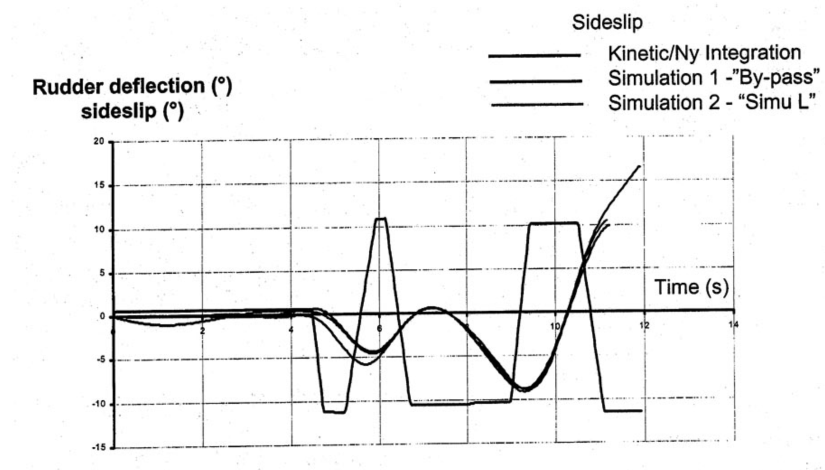
Rudder-Induced Operational Loads

AA587 Accident ; Airbus A300-600

(a) RUDDER AND SIDESLIP



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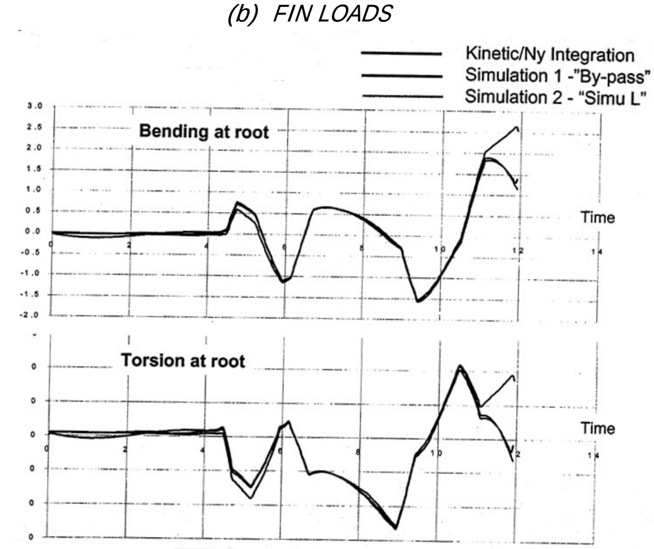
AA587 Accident ; Airbus A300-600

(b) FIN LOADS



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A300-600 ; In-Service Incident History

	Airline	MSN	Flight /date	Speed (Vcas)	Event	Ny (g)	Mx, fin root	Inspection
1	AAL	420	Flt 587 NY Nov-01	250	Rudder reversals	0.38	1.82 LL	Accident
2	AAL	643	Miami Mar-99	180	Rudder oscillations	0.32	1.16 LL	Completed : no findings
3	AAL	513	Flt 903 Florida May-97	190 - 230	Stall departure ; several rudder doublets	0.55 & 0.7	1.53 LL (1st doublet) & well beyond UL (est) subsequently (no DFDR data)	Completed : Local damage at rear r.h.s fin attach.
4	AAL	469	Flt 1193 May-89	250	Rudder jerk	0.38	1.11 LL	Completed : no findings
5	Fedex	735	Flt 3407	220	Rudder trim runaway	0.33	0.8 LL	Not recommended
6	Fedex	745	Flt 1416 Nov-99	225 - 290	Rudder trim runaway	0.21	0.6 LL	No
7	KAL / FDX	447	Flt KE628 Nov-98		Inadvertent thrust reverser deployment	0.21	0.86 LL	Completed : no findings

Note : Load levels unknown at time of incidents, with no ability to easily develop load levels from DFDR data. All estimates of recent Origin.

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A310 ; In-Service Incident History

	Airline	MSN	Flight /date	Speed (Vcas)	Event	Ny (g)	Mx, fin root	Inspection
1	AFR	551	AFR825 Nov-99	275	Rudder trim runaway + "loss of control"	0.49	1.06 LL	Completed : no findings
2	SIA/BBC	433	Flt 427 Sep-92	290 - 425	Rudder trim runaway + "loss of control"	0.32	0.8 LL	Not recommended
3	IFL	503	Flt 103 Feb-91	50 - 300	3 stalls in go-round (looping) with loss of control and repetitive rudder inputs	0.36 & 0.69	1.55 LL 1.35 LL	Completed : no findings
4	ROT	636	Flt 381 Sep-94	160 - 180	Stall in go-round	0.37	1.12 LL	Completed : no findings

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Issues Raised by AA587 Accident

- Adequacy of structural design criteria for rudder maneuvers :
  - additional strength by consideration of rudder doublet, or other more severe maneuver ?
  - How many reversals to be considered ?
- Pilot awareness / training on the consequences of multiple rudder reversals :
  - aircraft response, including delayed roll effects
  - possibility of structural overload
- Systems design criteria :
  - rudder system sensitivity (lack of pilot feedback, possible pilot induced oscillation)
  - Optimal yaw damper architecture
- Other :
  - carbon composite construction and failure modes
  - effects of wake vortex encounter

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FAA Actions post-AA587

- AD 2001-23-51 ; Emergency Airworthiness Directive
  - visual inspection of all A310 / A300-600 fins in 15 days
  - no findings
- AA903 incident review
  - ultrasonic inspection finds delamination at one rear attach lug.
- Fleet-wide Loads Review
  - Loads analysis methods developed based on FDR parameters
  - AA903 (Ship 513) believed to have seen fin loads approaching ultimate
  - 6 other A310 / A300-600 identified based on in-service event analysis
  - detailed inspections provide no additional findings
- AD 2002-06-09 ; Supplementary Structural Inspections
  - Special inspection requirement if Ny > 0.3g in service
  - Extent of inspection to be based on loads analysis and initial inspections
- Rudder Events Survey / Monitoring

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NTSB Actions post-AA587

- NTSB SR A-02-01 / A-02-02 & Operations Bulletins
  - address need for pilot knowledge and training on use of rudder
- NTSB A-03-41
  - requires manufacturers to review AMM inspection criteria after possible exposure to high +/- vertical loads and lateral loads in severe turbulence or extreme maneuvering.
- NTSB A-03-42
  - requires manufacturers to set vertical and lateral load thresholds beyond which manufacturer oversight is required before returning airplane to service.
- NTSB A-03-43
  - requires operators to immediately notify FAA of possible high-load incidents.
- NTSB A-03-44
  - requires manufacturers to notify certification authorities of any high-load incident necessitating intervention by the manufacturer, providing load assessment and inspection results.

Pilot Instructions : AFM Operating Limitations

25.1583 Operating limitations

(a) Airspeed limitations. The following airspeed limitations and any other airspeed limitations necessary for safe operation must be furnished:

..(3) The maneuver speed, V_A, and a statement that full application of rudder and aileron controls, as well as maneuvers that involve angles of attack near the stall, should be confined to speeds below this value.

- Applies for single axis control inputs – roll, pitch or yaw.
- But does <u>not mean</u> that unlimited multiple control reversals are permissible below V_A speed
- And is usually not relevant for rudder control, because we are designed for yaw maneuvers (a single full input) at all speeds from V_{MC} to V_D, and loads are likely to be similar at any speed above the threshold for rudder limiter activation.

Pilot Advisories / Training

Extract from Airbus A310 / A300-600 FCOM Bulletin 15/1
(similar from other manufacturers)

- Approved use of rudder
  - Takeoff / landing / landing roll
  - Minor inputs for low speed turn coordination, if necessary
  - To counter asymmetric thrust
  - Certain control system malfunctions (rudder trim runaway, aileron jam..)
  - Landing gear unsafe indication
- Non-approved use of rudder
  - To induce roll
  - To counter roll induced by turbulence
  - To counter dutch roll in the event of yaw damper failure.

…"Whatever the flight condition may be, aggressive, full or nearly full, opposite rudder inputs must not be applied. Such inputs can lead to loads higher than the limit, or possibly the ultimate loads and can result in structural damage or failure. The rudder travel limiter system is not designed to prevent structural damage or failure in the event of such rudder system inputs."

…."Rudder reversals must never be incorporated into airline policy, including so-called 'aircraft defensive maneuvers' to disable or incapacitate hijackers."

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Safety Enhancement through Information Exchange

- Incidents of current particular interest:
  - Any high fin load (due to sideslip, rudder, or combination)
  - High fin loads due to rudder activity ("a rudder event")
- Events which meet certain criteria are flagged for detail review.
  - Anonymous "de-sensitized" flight records shared through an agreed third party (IATA).
  - Pilot reports also provided for context and for details of circumstance.
  - Unusual and infrequent events only : Low subscriber workload.

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Recommendation for FDM

Institute event monitoring and incident reporting for exceedences of threshold values of:

1. Lateral acceleration [N_Y = 0.2 ~ 0.25g]
2. Rudder load [function of rudder angle and speed]

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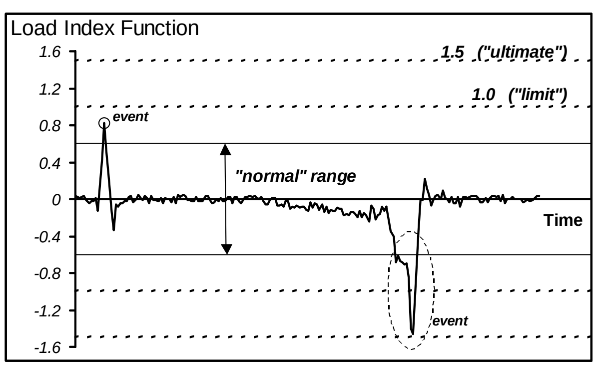
Load Index Functions

A calculated function of measured flight parameters which approximates a key structural load, and which can be monitored for exceedence of a triggering threshold value.

- 1.0 approximates the largest load an aircraft might ever see, once a lifetime
- 1.5 approximates failing load
- Normal range of vertical tail loading is small – high fin loads are unusual



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Load Index 1
Aircraft Lateral Acceleration, Ny

- By direct monitoring of a measured parameter.
- High lateral acceleration is indicative of a large total aerodynamic side force:
  Ny x Gross weight = Total aerodynamic side force
- Fin load is a high percentage of total side force
  - Typically around 70% of total
  - But index gives no information about fin load distribution
- INDEX = Ny (g's)
- Suggested event trigger : Ny > ±0.2 g

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Load Index 2
Rudder Load

- Captures any instance of large rudder loads due to combination of airspeed and control deflection.
  - Is not triggered by full rudder use during approach/landing
- INDEX = $V_E^2.\delta r$ / 770000
  where: V_E = Equivalent airspeed (knots)
  δr = rudder position (deg)
- Suggested event trigger : Index > ±0.6

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